

The Bounded Edge Coloring Problem and Offline Crossbar Scheduling

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Abstract

This paper introduces a variant of the classical edge coloring problem in graphs that can be applied to an offline scheduling problem for crossbar switches. We show that the problem is *NP*-complete, develop three lower bounds on the optimal solution value and evaluate the performance of several approximation algorithms, both analytically and experimentally. We show how to approximate an optimal solution with a worst-case performance ratio of $3/2$ and our experimental results demonstrate that the best algorithms produce results that very closely track a lower bound.

1 Introduction

An instance of the *bounded edge coloring problem* is an undirected graph $G = (V, E)$ with a positive integer *bound* $b(e)$ for each edge e . A *bounded edge coloring* is a function c , from the edges to the positive integers, with $c(e) \geq b(e)$ for all edges e and $c(e_1) \neq c(e_2)$ for all edge pairs e_1 and e_2 that have an endpoint in common. The objective of the problem is to find a coloring in which the largest color is as small as possible. An example is shown in Figure 1; the first number labelling each edge is its bound, while the second is a valid color.

In this paper, we focus on a restricted version of the problem in which the graph is bipartite, with the vertices divided between *inputs* and *outputs*.

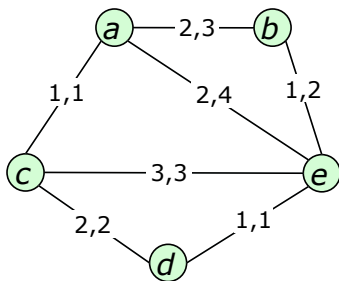


Figure 1: Example of bounded edge coloring

We also are usually interested in graphs where the bounds on the edges incident to each input are unique; we refer to this as the *unique input bounds condition*. An example of a graph that satisfies the unique input bounds condition is shown in Figure 2. The right side of the figure shows a tabular representation of the graph, where each row corresponds to an input, each column corresponds to an output and each integer denotes an edge and its bound. Note that this graph requires colors $[1 \dots 5]$.

The bounded edge coloring problem is an abstraction of an offline version of the crossbar scheduling problem. In this application, the graph's vertices represent the inputs and outputs of a crossbar switch, while the edges represent packets to be transferred from inputs to outputs. The edge bounds represent the arrival times of the packets and the colors represent the times at which packets are transferred from inputs to outputs. Since an input can only receive one packet at each time step, the inputs naturally satisfy the unique input bounds condition. The objective of the problem is to transfer all packets across the crossbar in the smallest possible amount of time.

The crossbar scheduling problem has been studied extensively in the on-line context, using several distinct performance criteria. For so-called *input queued* switches, the focus has been on ensuring bounded waiting times in systems subjected to random input traffic. Many scheduling algorithms have been shown to meet this objective [6, 7, 8]. More compelling, worst-case results have been shown for *combined input and output queued* switches, in which the crossbar is capable of transferring packets somewhat faster than

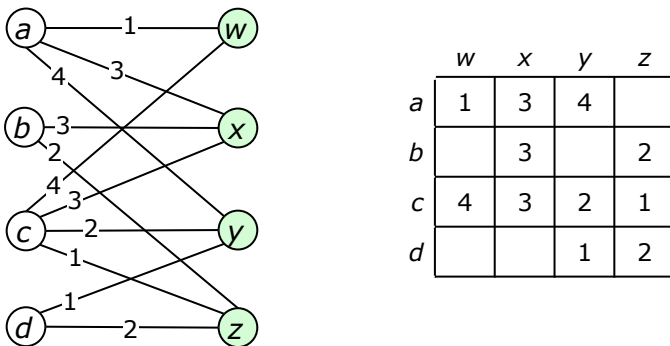


Figure 2: Bipartite instance that satisfies the unique input bounds condition

they can arrive at the inputs, or be transmitted from the outputs. Some scheduling algorithms can match the performance of an idealized *output-queued* switch when the crossbar is twice as fast as the inputs and outputs [1, 4, 5].

In section 2, we show that the bounded edge coloring problem is *NP*-complete. In section 3 we derive several lower bounds on the number of colors required, and introduce a class of graphs which require substantially more colors than implied by the weaker of our lower bounds. In section 4, we describe several algorithms and establish worst-case performance ratios for some. Experimental performance results appear in section 5.

2 Complexity of Bounded Edge Group Coloring

For the ordinary edge coloring problem, we can color any bipartite graph with colors $[1 \dots \Delta]$, where Δ is the maximum vertex degree [2]. Unfortunately, the bounded edge coloring problem is *NP*-complete. We can show this, using a reduction from the *partial edge coloring completion problem* for bipartite graphs. In this problem, we are given a bipartite graph with some of its edges colored, and are asked to complete the coloring using no color larger than a given integer k . This is a generalization of the *partial latin squares completion problem* shown to be *NP*-complete in [3].

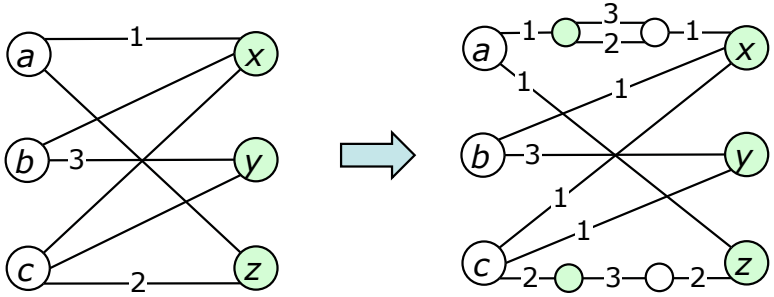


Figure 3: Reduction from edge coloring completion to bounded edge coloring

Let $G = (V, E)$ be a bipartite graph, with partial coloring c , using colors $1, \dots, k$. We construct a second bipartite graph $H = (W, F)$ where W includes all vertices in V , plus some additional vertices to be specified shortly. Each uncolored edge in E is included in F and is assigned a lower bound of 1. Each edge in E that is colored k is included in F and assigned a lower bound of k . For each edge in E that is colored $k - 1$, we include a chain of three edges, with the inner edge assigned a lower bound of k , while the outer two edges are assigned lower bounds of $k - 1$. For each edge in E that is colored $k - i$, for $i > 1$, we include a similar component with two additional vertices, two “outer” edges and i parallel edges joining the two added vertices. The outer edges are assigned lower bounds of $k - i$, while the inner edges are assigned lower bounds of $k - i + 1, \dots, k$. The construction of the chains guarantees that in any valid k -coloring of H , the outer edges are assigned the same color that the corresponding edge was assigned in G . The uncolored edges in G are free to use any color in $1, \dots, k$. This construction is illustrated in Figure 3 for the case of $k = 3$. It’s straightforward to show that the partial coloring of G can be completed using colors $1, \dots, k$ if and only if H can be colored using colors $1, \dots, k$.

Unfortunately, while this reduction does show that bounded edge coloring is *NP*-complete, the graph H does not satisfy the unique input bounds condition. To show that instances that satisfy this condition are also hard to solve, we need to use a more elaborate reduction. The new reduction

starts with the graph H constructed above, and then adds $2k$ to the lower bounds specified earlier for the components constructed to handle the pre-colored edges in the original partial edge coloring instance. For edges that are uncolored in G and incident to an input u , the corresponding edges in H are assigned distinct lower bounds in the range $k + 1, \dots, 2k$. We then attach an additional component to u that has the effect of forcing these edges to have colors larger than $2k$. This construction is illustrated in Figure 4. This component has two groups of parallel edges joining a pair of vertices

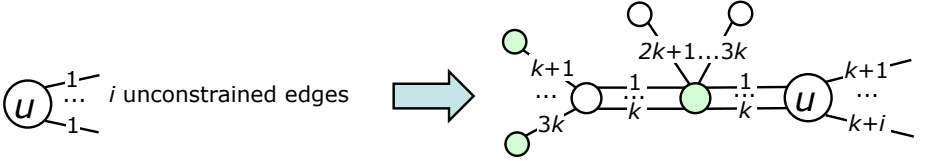


Figure 4: Additional component for each input

to the original input u ; these edge groups are each assigned lower bounds of $1, \dots, k$. There are two other groups joining additional leaf vertices to the first two vertices. One group of “leaf edges” has lower bounds of $k + 1, \dots, 3k$ and must be assigned colors equal to their bounds in any valid coloring with a maximum color of $3k$. The other has bounds $2k + 1, \dots, 3k$ and must also be assigned colors equal to their bounds in any valid coloring with a maximum color of $3k$. This means that the k parallel edges incident to u must be assigned colors $k + 1, \dots, 2k$ and this in turn forces the edges that were uncolored in G to have colors larger than $2k$ in the modified version of H . Figure 5 shows the final version of H , for the example in Figure 3. Observe that all input vertices in the final version of H do in fact have unique lower bounds. It’s straightforward to show that the final version of H can be colored using colors $1, \dots, 3k$ if and only if G ’s coloring can be completed using colors $1, \dots, k$.

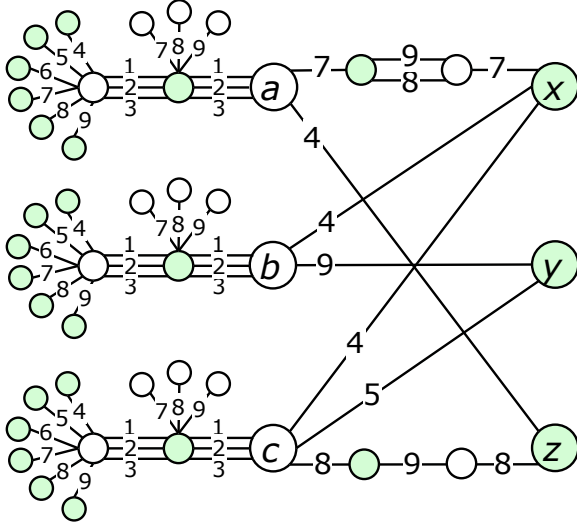


Figure 5: Extension of example in Figure 3

3 Lower Bounds

In this section, we present several methods to compute lower bounds on the maximum edge color used by an instance of the bounded edge-coloring problem. The first is referred to as the *degree bound*. Before describing it, we need a few definitions. For any vertex u in a graph G , let $\delta_G(u)$ denote the number of edges incident to u (the vertex degree) and let $\Delta_G = \max_u \delta_G(u)$. If G is an instance of the bounded edge coloring problem, we let G^k be the subgraph of G containing edges with bounds $\geq k$ and we let G_k be the subgraph containing edges with bounds $\leq k$.

Observe that if a vertex u has d edges with bounds $\geq c$, then some edge incident to u must be assigned a color $\geq c + d - 1$. Consequently, for any k , the number of colors needed to color G^k is at least $k + \Delta_{G^k} - 1$. The degree bound for G is denoted $D(G)$ and defined by $D(G) = \max_k k + \Delta_{G^k} - 1$. For the graph in Figure 2, $D = 5$ and this graph can be colored using colors $1, \dots, 5$. Some graphs require more than D colors. Figure 6 shows a graph

	<i>e</i>	<i>f</i>	<i>g</i>	<i>h</i>	<i>i</i>	<i>j</i>	<i>k</i>
<i>a</i>	1				2,3,4		
<i>b</i>	1	2				3,4	
<i>c</i>	1	2	3				4
<i>d</i>	1	2	3	4			

	<i>e</i>	<i>f</i>	<i>g</i>	<i>h</i>	<i>i</i>	<i>j</i>	<i>k</i>
<i>a</i>	5				2,3,4		
<i>b</i>	1	5				3,4	
<i>c</i>	2	3	5				4
<i>d</i>	4	2	3	5			

Figure 6: D colors are not always enough (top table shows edge bounds, bottom shows colors in an optimum coloring)

(in the tabular format) with $D = 4$ that requires five colors (an optimal coloring is shown in the second table).

The graph in Figure 6 is actually a special case of a class of graphs that require substantially more than D colors. The graph B_n has inputs u_1, \dots, u_n and outputs v_1, \dots, v_{2n-1} . For $1 \leq i \leq n$, $1 \leq j \leq i$, there is an edge (u_i, v_j) with bound j , and for each $1 \leq i < n$, $i < j \leq n$, there is an edge (u_i, v_{n+i}) with bound j . Figure 7 shows the case of B_7 , along with a coloring using nine colors. Note that in general, $D_{B_n} = n$.

Our second lower bound is obtained by computing a sequence of matchings. Observe that for any integer k , the edges of G that are colored k must form a matching in G_k . If we let m_k be the number of edges in a maximum size matching of G_k , then $m_1 + m_2 + \dots + m_k$ is an upper bound on the number of edges that can be assigned colors in $1, \dots, k$. If this sum is less than the number of edges in G , then G requires more than k colors. So,

	A	B	C	D	E	F	G	H	I	J	K	L	M
a	1							2-7					
b	1	2							3-7				
c	1	2	3							4-7			
d	1	2	3	4							5-7		
e	1	2	3	4	5							6-7	
f	1	2	3	4	5	6							7
g	1	2	3	4	5	6	7						

	A	B	C	D	E	F	G	H	I	J	K	L	M
a	9							2-7					
b	8	9							3-7				
c	2	8	9							4-7			
d	1	2	8	9							5-7		
e	3	4	5	8	9							6-7	
f	6	3	4	5	8	9							7
g	7	6	3	4	5	8	9						

Figure 7: Graph B_7 and a valid edge coloring using colors $1, \dots, 9$

if we let $M(G)$ be the smallest integer k for which $m_1 + m_2 + \dots + m_k$ is greater than or equal to the number of edges in G , then $M(G)$ is a lower bound on the number of colors required to color G . We refer to M as the *matching bound*. For the graph B_4 in Figure 6, the sequence of matching sizes is 1, 3, 4, 4, 4 and consequently, $M = 5$. For the graph B_7 in Figure 7, the sequence of matching sizes is 1, 3, 5, 7, 7, 7, 7, 7, 7 and $M = 9$. It's not difficult to show that in general, the matching bound for B_n is $\lceil 5n/4 \rceil$.

Now, we turn to our third lower bound. Let $G = (V, E)$ be a bipartite graph with edge bounds $b(e)$ and let c be a valid coloring of G using colors $1, \dots, C$. Let H_k be the subgraph of G that is colored using colors $1, \dots, k$

and let J_k be the subgraph of G that is colored using colors $k + 1, \dots, C$. Note that H_k is a subgraph of G_k , $D_{H_k} \leq k$ and $\Delta_{J_k} \leq C - k$. So, for any k , it is possible to split G into two subgraphs that have these properties. Now, let C' be an integer smaller than C and note that if there is some k , for which we cannot split G into subgraphs H_k and J_k with H_k a subgraph of G_k , $D_{H_k} \leq k$ and $\Delta_{J_k} \leq C' - k$, then G cannot be colored using only colors $1, \dots, C'$. This leads to a lower bound on the number of colors needed to color a given graph.

To make this bound useful, we need an efficient way to partition G into subgraphs H_k and J_k for given integers k and C . This can be done by solving a network flow problem. Let $F_{k,C}$ be a *flow graph* that includes a *source vertex* s , a *sink vertex* t and a chain of vertices for each vertex in G_k . Specifically, for each input u in G_k , $F_{k,C}$ contains a chain consisting of vertices u_i for each $i \in \{1, \dots, k\}$ and edges (u_i, u_{i+1}) with *capacity* $k - i$. There is also an edge from s to u_1 with capacity k . For each output v in G_k , $F_{k,C}$ contains a chain consisting of vertices v_i for each $i \in \{1, \dots, k\}$ and edges (v_{i+1}, v_i) with *capacity* $k - i$. There is also an edge from v_1 to t with capacity k . For each edge (u, v) in G_k with bound i , F contains an edge (u_i, v_i) of capacity 1. We refer to this last set of edges as the *core edges* of $F_{k,C}$. Observe that the subset of the core edges that have positive capacity in any integer flow on $F_{k,C}$ correspond to a subgraph of G_k that has a degree bound D that is no larger than k . To complete the construction of $F_{k,C}$, we specify *minimum flow requirements* for the edges incident to s and t . In particular, for input u of G , the edge (s, u_1) is assigned a minimum flow of $\min\{0, \delta_G(u) - (C - k)\}$. Similarly, for output v of G , the edge (v_1, t) is assigned a minimum flow of $\min\{0, \delta_G(v) - (C - k)\}$. Given an integer flow on F_k that satisfies the minimum flow requirements, we define H_k to consist of those edges in G that correspond to core edges that have positive flow. We define J_k to include the remaining edges in G . It is straightforward to show that H_k is a subgraph of G_k , $D_{H_k} \leq k$ and $\Delta_{J_k} \leq C - k$. If there is no integer flow on F_k that satisfies the minimum flow requirements, then G cannot be colored using only colors $1, \dots, C$.

Figure 8 shows the graph B_4 and the corresponding flow graph $F_{2,5}$. There is an integer flow for $F_{2,5}$ that uses the edges that are emphasized in

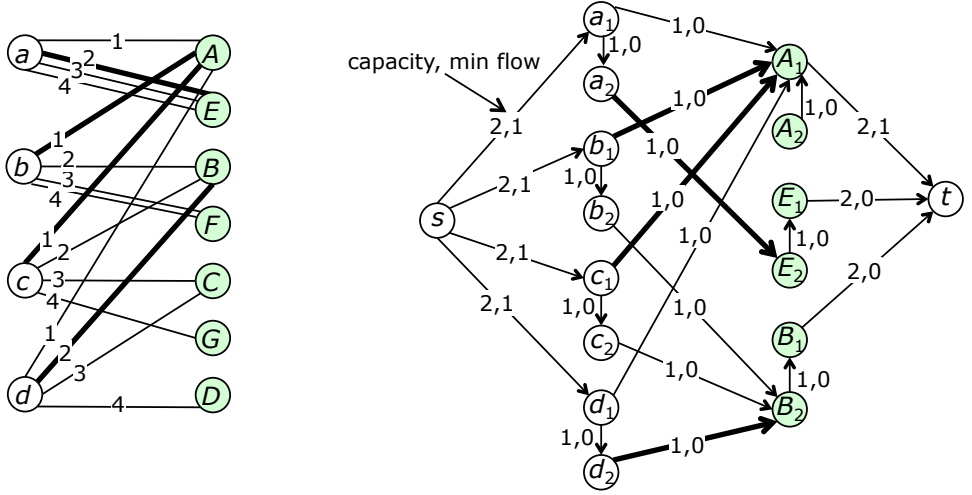


Figure 8: Graph B_4 and corresponding flow graph $F_{2,5}$

“**bold**” and satisfies all the minimum flow requirements. The edges of B_4 that correspond to the bold core edges are also emphasized in bold. These edges define the graph H_2 , while the remaining edges define J_2 . Note that $D_{H_2} = 2$ and $\Delta_{J_2} = 3$.

The *flow bound* for G is denoted by P_G and is defined as the smallest value of C for which $F_{k,C}$ has a flow that satisfies the minimum flow requirements, for all values of $k \in [1, b_{\max}]$, where b_{\max} is the largest edge bound in G . The flow bound for B_8 is 11, while the matching bound is 10. This gap increases for larger graphs. For example, B_{64} has a matching bound of 80 and a flow bound of 83, while B_{256} has a matching bound of 320 and a flow bound of 331.

We close this section by describing a general method for coloring graphs B_n using colors $1, \dots, n + \lceil (n-1)/3 \rceil$. For B_{64} the largest color is 85, for B_{256} the largest color is 341. Figure 9 illustrates the method for coloring B_n . The top part of the figure shows the coloring given earlier for B_7 , with several regions of the table highlighted. Note that each of the four highlighted regions uses a distinct set of colors and each color used is repeated along a

	A	B	C	D	E	F	G	H	I	J	K	L	M
a	9							2-7					
b	8	9							3-7				
c	2	8	9							4-7			
d	1	2	8	9							5-7		
e	3	4	5	8	9							6-7	
f	6	3	4	5	8	9							7
g	7	6	3	4	5	8	9						

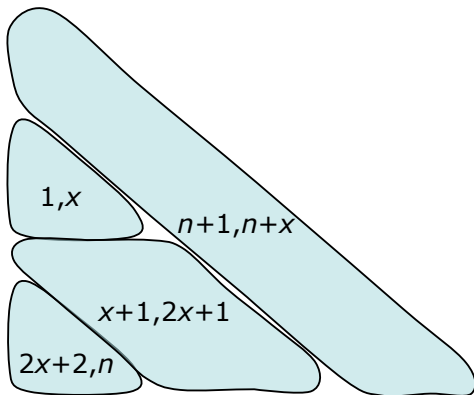


Figure 9: General method for coloring B_n

diagonal within the region. The edges incident to the outputs H, \dots, M are assigned colors equal to their bounds. The bottom part of the figure shows how the colors of the edges incident to the first n outputs are assigned in the general case, using a parameter $x = \lceil (n-1)/3 \rceil$. Again, we divide the table defining the edges into four regions and assign disjoint sets of colors to those regions. Within each region, colors are used repeatedly along diagonals. The edges incident to the last $n-1$ outputs are assigned colors equal to their bounds. The choice of x ensures that the assignment of colors to edges yields a legal coloring of the graph that respects all the edge bounds.

4 Approximate algorithms

In this section, we describe several approximate algorithms for the bounded edge coloring problem and analyze their worst-case performance. Let $G = (V, E)$ be a graph with edge bounds $b(e)$ and let $C^*(G)$ be the largest color value used by an optimal solution.

We start with a very simple method that produces solutions with a maximum color $\leq 2C^*$. Let b_{\max} be the largest color bound used by an instance of the bounded edge coloring problem and let Δ be the maximum vertex degree. Using any method for the ordinary edge coloring problem, we can color the edges using colors $b_{\max}, \dots, b_{\max} + \Delta - 1$ and since $C^* \geq \max\{b_{\max}, \Delta\}$, the largest color used by this solution is $< 2C^*$.

We can get a better approximation by first splitting G into two subgraphs and coloring each of the subgraphs separately. Consider an optimal coloring of G and let H_k be the subgraph defined by the edges with colors $\leq k$. Note that H_k is a subgraph of G_k and that $\Delta_{H_k} \leq k$. If we let J_k be the subgraph of G defined by the edges with colors $> k$, then $\Delta_{J_k} \leq C^* - k$. So an optimal coloring must be divisible into a pair of subgraphs that satisfy these inequalities. Note that we can color H_k using colors $k, \dots, 2k - 1$ using any algorithm for the ordinary edge coloring problem. We can also color J_k using colors $b_{\max}, \dots, b_{\max} + C^* - (k + 1)$. So long as $2k - 1 < b_{\max}$, these two sets of colors do not overlap meaning that we can color the entire graph using colors $k, \dots, b_{\max} + C^* - (k + 1)$. If we let $k = \lfloor b_{\max}/2 \rfloor$, the largest color is $\leq (b_{\max}/2) + C^* \leq (3/2)C^*$.

In order to construct an approximation algorithm based on this observation, we need a way to split G into subgraphs H_k and J_k . This can be done by solving the same flow problem that was used in the flow lower bound computation. Alternatively, we can simplify the flow problem by collapsing each of the input-side chains u_1, \dots, u_k into a single vertex u and each of the output-side chains v_1, \dots, v_k into a single vertex v . Thus, we can efficiently color any graph G using colors $\leq (3/2)C^*$. We'll refer to this as the *splitting method*.

Our next algorithm is a simple greedy algorithm that repeats the following step until all edges are colored.

Select an edge $e = (u, v)$ and let c be the smallest color that is at least as large as $b(e)$ and is not yet in use at both u and v .

We select edges that are incident to a vertex of maximum degree in the uncolored subgraph. While we have no worst-case-performance bound for this algorithm, in practice it out-performs the splitting method, as we will see in the next section.

Now, we consider an algorithm based on the classical augmenting path algorithm for the ordinary edge coloring problem. For the bounded edge coloring problem, a path p is an *ij-augmenting path* if its edges alternate in color between i and j , it cannot be extended any further at either of its endpoints and every edge in the path has a bound that is $\leq \min\{i, j\}$. The *augmenting path algorithm* for the bounded edge coloring problem colors the edges by repeatedly selecting an edge $e = (u, v)$ and then applying the first case from the following list that applies.

- If there is some *eligible color* that is unused at both endpoints, color e with one such color.
- If there are eligible colors i and j , where i is available at u and j is available at v , and there is an *ij-augmenting path* starting at v , then reverse the colors of the edges on the path and let $c(e) = i$.
- If there are eligible colors i and j , where i is available at u and j is available at v , and there is a *ji-augmenting path* starting at u , then reverse the colors of the edges on the path and let $c(e) = j$.
- Allocate a new eligible color and use it to color e .

Initially, colors $1, \dots, b_{\max}$ are eligible. New colors are allocated sequentially, as needed. We select edges that are incident to a vertex of maximum degree in the uncolored subgraph. When selecting colors, we give preference to colors with smaller values. In the first case, we select the smallest eligible color that is unused at both endpoints. In the second and third cases, we select color pairs i and j that minimize $\max\{i, j\}$.

Since the augmenting path algorithm for the ordinary edge-coloring problem uses Δ colors, this version colors uses no color larger than $b_{\max} + \Delta - 1$.

We can also use it to color the subgraphs in the splitting method to obtain an algorithm that uses no color larger $(b_{\max}/2) + C^*$.

Next, we consider algorithms based on constructing a series of matchings. The first such algorithm starts by initializing $k = 1$ then repeating the following step so long as there are uncolored edges.

Find a maximum size matching on the uncolored edges in G_k , assign color k to all edges in the matching, then increment k .

We refer to this as the *maximum size matching* algorithm. We can improve it by selecting matchings that maximize the number of matched vertices that have maximum degree in the uncolored subgraph. This can be done using an algorithm described in [10]. This version of the matching algorithm is called the *maximum degree matching* algorithm. Reference [10] also shows how to find maximum size matchings that maximize a general *priority score* based on arbitrary integer priorities assigned to the vertices. Our third matching algorithm uses this method. Priorities are assigned in decreasing order of vertex degree in the uncolored subgraph. So, vertices of maximum degree are assigned priority 1, those with the next largest degree are assigned priority 2 and so forth. We refer to this version of the matching algorithm as the *priority matching* algorithm. The last two of the matching algorithms use no color larger $b_{\max} + \Delta - 1$. Also, like the augmenting path algorithm, they can be used with the splitting method to obtain an algorithm that uses no color larger $(b_{\max}/2) + C^*$.

5 Experimental Evaluation

In this section, we evaluate the performance of the algorithms introduced in the last section, experimentally. We start, by evaluating the performance using random graphs that are generated using the following procedure.

- Generate a random regular bipartite graph, with n inputs, n outputs and all vertices having degree Δ .
- At each input, assign the incident edges a unique random color in $1, \dots, b_{\max}$, where $b_{\max} \geq \Delta$

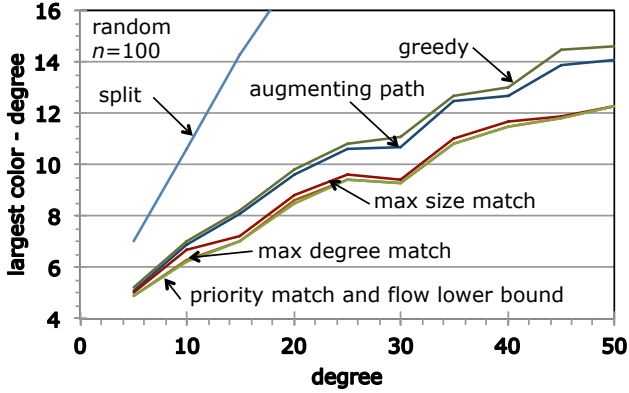


Figure 10: Performance results for random instances

This produces a random problem instance that satisfies the unique input bounds condition. Figure 10 shows results for graphs on 100 vertices where the vertex degree is varied from 5 to 50 and $b_{\max} = \Delta + 3$. The y -axis displays the difference between the maximum color used and the vertex degree. Each data point shows the average from ten random problem instances. Error bars have been omitted for clarity, but the relative error was generally less than 2%.

The lowest curve shows the results for the flow lower bound and the priority matching algorithm (for these graphs, the priority matching algorithm always produced results equal to the bound). The maximum degree matching algorithm was almost identical to the priority matching algorithm, but did occasionally exhibit small differences. The maximum size matching algorithm was not quite as good as the other two. The greedy and augmenting path algorithms also produced perfectly respectable results, generally exceeding the largest color used by the priority matching algorithm by less than 5%.

Figure 11 shows performance results for the graphs B_n . Here the max degree and priority match algorithms generally use just 2 or 3 more colors than the number given by the flow lower bound. The maximum size match-

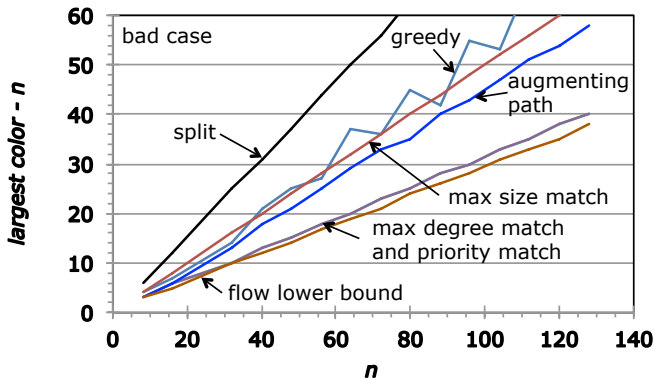


Figure 11: Performance results for B_n

ing algorithm performs less well in this case, actually under-performing the augmenting path algorithm.

The algorithms described here are all available as part of an open-source library of graph algorithms and data structures [9].

6 Closing Remarks

The bounded edge-coloring problem is a natural generalization of the ordinary edge-coloring problem and interesting in its own right, independent of its application to the crossbar scheduling problem. There is a considerable gap between the best worst-case performance ratio achieved by our algorithms and the experimental performance measurements. Closing that gap is the main open problem to be addressed.

It's worth noting that most of our algorithms can be applied to general graphs, as well as bipartite graphs. It would be interesting to understand how they perform in this context. Unfortunately, the flow lower bound cannot be applied to general graphs, although the degree bound and matching bound can be.

While our results do not apply directly to the online version of the cross-

bar scheduling problem, there is potential for extending them to make them more applicable. For example, one can model systems in which the crossbars operate at faster speeds than the inputs and outputs by restricting the values allowed as edge bounds. This can be used to derive a lower bound on the “speedup ratio” needed to match the performance of an ideal output-queued switch.

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